Opportunities for synergy between experiments and BOUT++ modeling on Alcator C-Mod and DIII-D

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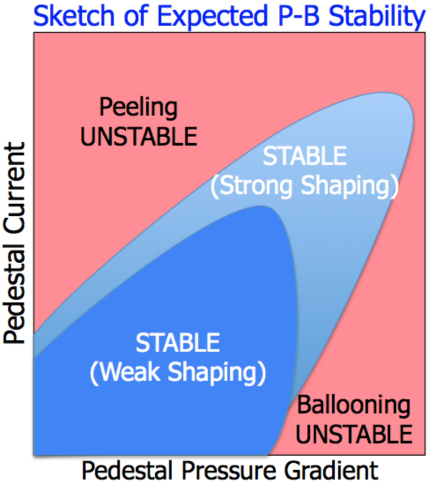
Outline

- The plasma edge sets boundary conditions on the core plasma and needs to be understood
- BOUT++ is a maturing code, able to simulate an increasingly broad range of physical regimes
- $\nu^* > 1$: Alcator C-Mod's EDA H-mode
  - Linear: stability analysis
  - Nonlinear: comparison to experimental measurements
- $\nu^* < 1$: DIII-D's ELM-free H-mode
  - BOUT++ gyro-Landau fluid code is desired to aid the interpretation of experimental measurements
- Conclusions and future work

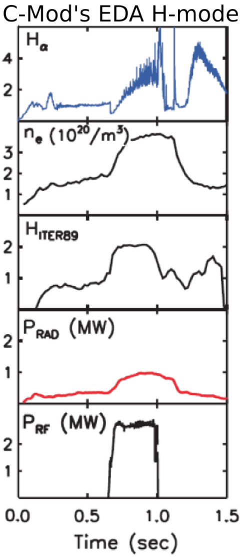
The "Standard Model": Peeling-Ballooning (PB) modes constrain the pedestal in ELMy H-mode



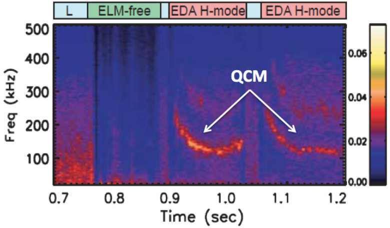
- Peeling and ballooning modes *couple* at intermediate $5 \leq n \leq 25$ to drive ELMs
    - Ideal MHD instability
- Experimentally, ELMs are routinely observed when crossing the PB threshold
- Ideal MHD codes such as ELITE* can assess stability to PB modes

* P. B. Snyder et al. *Phys. Plasmas* **9** 2037 (2002).

C-Mod's EDA H-mode is a steady-state, high-performance regime regulated continuously by a QCM edge fluctuation

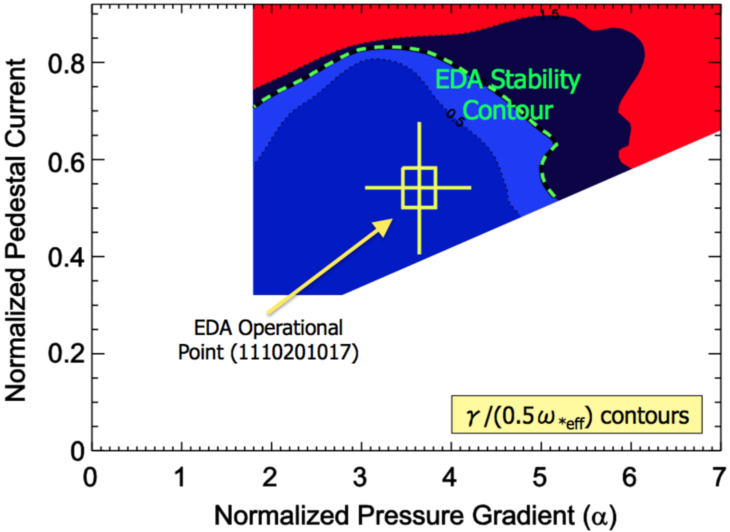


- The Enhanced D_α (EDA) H-mode* exhibits:
  - Excellent energy confinement
  - Reduced impurity confinement
- EDA is C-mod's "workhorse" H-mode
- EDA pedestal regulated by a quasi-coherent mode (QCM) oscillation $\sim 100\,\text{kHz}$
- $\nu^* > 1 \Rightarrow$ amenable to fluid analysis



* M. Greenwald et al. *Phys. Plasmas* **6** 1943 (1999).

ELITE shows that ideal PB modes are *stable* in EDA H-mode; other physics needed to explain the QCM



BOUT++ can solve a set of nonideal reduced MHD equations, including η effects important for $\nu^* > 1$

Reduced MHD Equations*

$$\frac{\partial \omega}{\partial t} + \mathbf{V_E} \cdot \nabla \omega = B_0^2 \nabla_{||} \left(\frac{J_{||}}{B_0} \right) + 2\hat{\mathbf{b}}_\mathbf{0} \times \boldsymbol{\kappa} \cdot \nabla p$$

$$\frac{\partial P}{\partial t} + \mathbf{V_E} \cdot \nabla P = 0$$

$$\frac{\partial A_{||}}{\partial t} = -\nabla_{||}(\phi + \boxed{\Phi_0}) + \boxed{\frac{\eta}{\mu_0} \nabla_\perp^2 A_{||}}$$

Non-ideal Physics
Include resistivity
After gyroviscous cancellation, the diamagnetic drift modifies the vorticity
Using force balance and assuming no net rotation, $E_{r0} = (1/n_i Z_i e)\nabla_\perp P_{i0}$

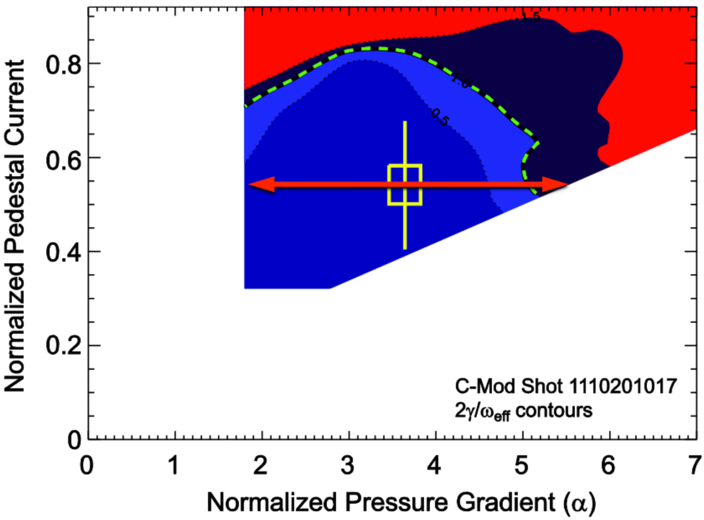
Definitions

$$\omega = \frac{n_0 m_i}{B_0} \left(\nabla_\perp^2 \phi + \boxed{\frac{1}{n_0 Z_i e} \nabla_\perp^2 p_i} \right), \qquad \mathbf{V_E} = \frac{1}{B_0} \hat{\mathbf{b}}_\mathbf{0} \times \nabla(\phi + \boxed{\Phi_0})$$

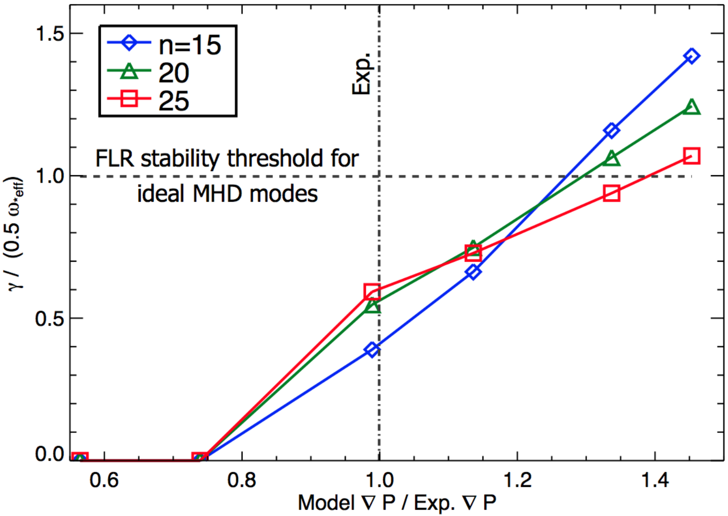
$$J_{||} = J_{||0} - \frac{1}{\mu_0} \nabla_\perp^2 A_{||}, \qquad P = P_0 + p$$

* B. D. Hazeltine and J. D. Meiss, *Plasma Confinement* (Dover, Mineola, NY, 2003).

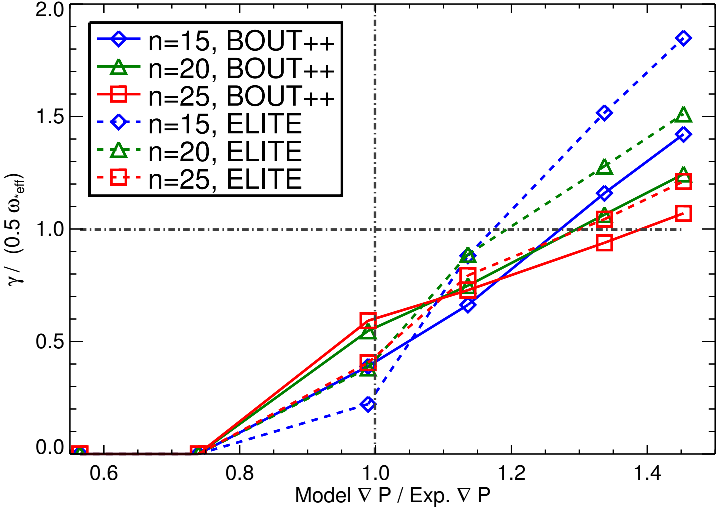
∇P was self-consistently varied to assess EDA's linear stability with BOUT++



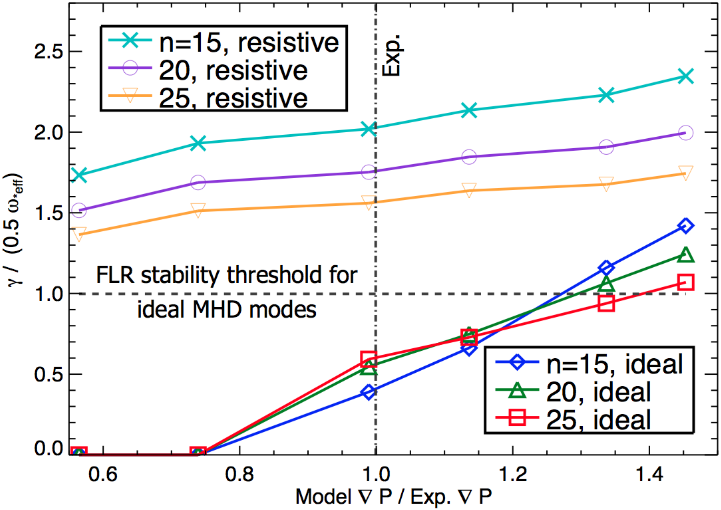
BOUT++ indicates PB modes are *stable* at experimental values of ∇P



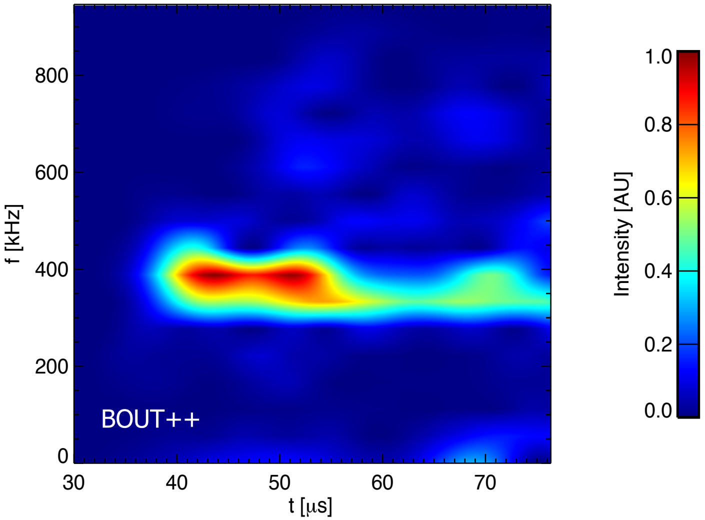
BOUT++ marginal stability thresholds and growth rate trends for PB modes agree with ELITE



C-Mod's resistivity drives unstable modes at experimental values of ∇P that may be responsible for the QCM



Nonlinear simulations show a quasi-coherent oscillation *qualitatively* similar to EDA's QCM



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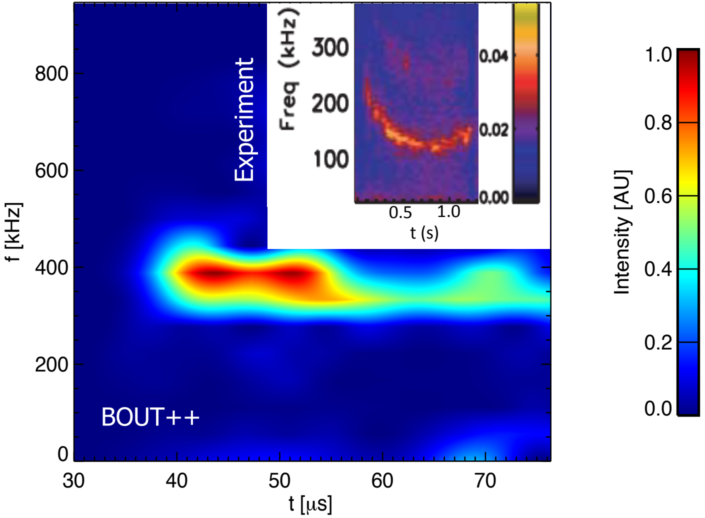
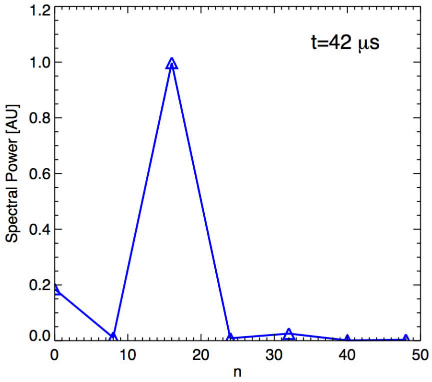
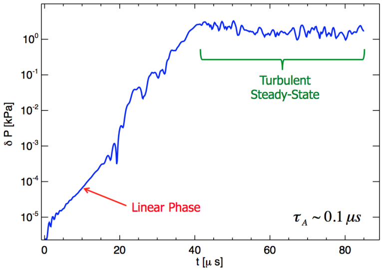


The nonlinear quasi-coherent oscillation is peaked about $n \sim 16$, similar to C-Mod's EDA QCM

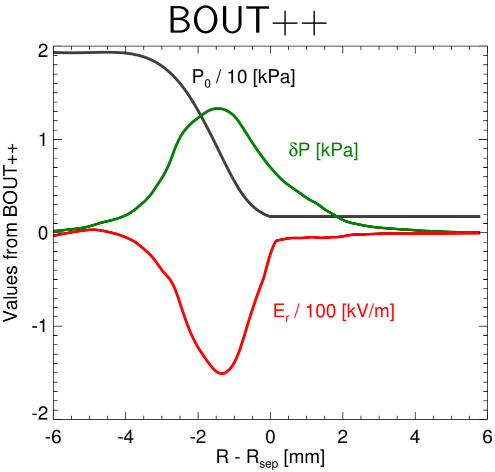
BOUT++ predicted toroidal mode spectrum



Nonlinear saturation occurs at $t \sim 40\,\mu s$, requiring $\sim 400\,\tau_A$



The nonlinearly computed mode spans the separatrix and sits in the edge E_r well, similar to previous modeling results



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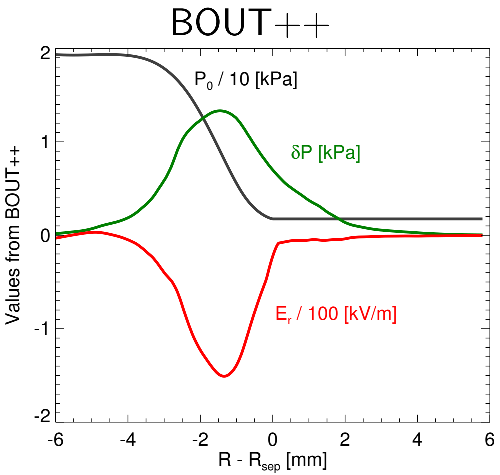
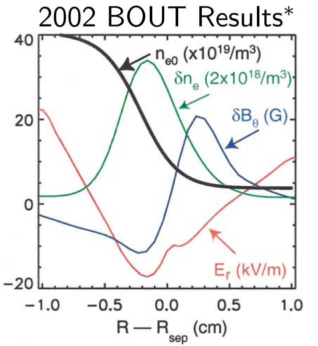
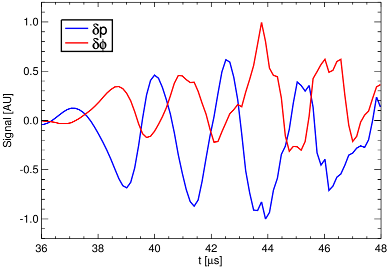




* A. Mazurenko et al. *Phys. Rev. Lett.* **89** 225004 (2002).

The pressure and potential fluctuations are *out* of phase, in contrast to recent QCM measurements

BOUT++ δp and $\delta\phi$ predictions:



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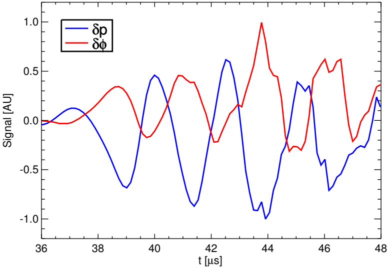
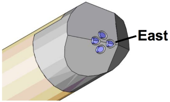


Mirror Langmuir Probe (MLP) Measurements*:



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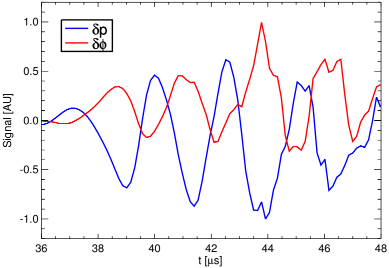

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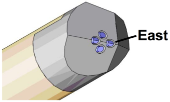

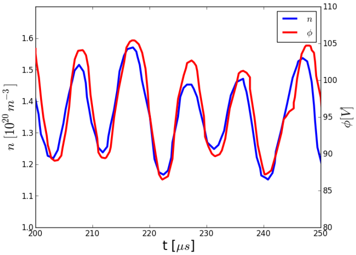

$\Rightarrow$ **Drift wave!**

*B. LaBombard et al. TTF Workshop, Santa Rosa, CA (Apr. 9-12, 2013).

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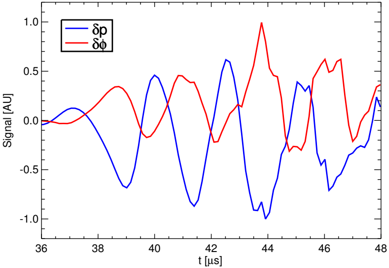

Hall term in Ohm's law for drift wave-like response may help:

$$\frac{\partial A_{||}}{\partial t} = -\nabla_{||}\Phi - \eta J_{||} + \boxed{\frac{1}{en}\nabla_{||} p_e}$$

or may need *2-fluid* model

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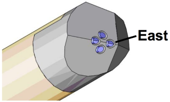

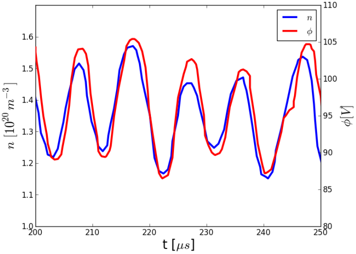

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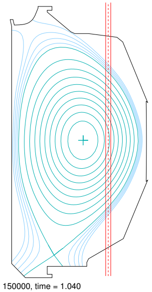
Gyro-Landau BOUT++ needed to interpret measurements in $\nu^* < 1$ regimes, e.g. DIII-D's ELM-free H-mode

- Phase Contrast Imaging (PCI) measures $\int \tilde{n} dl$
- Detector: 16 channel linear array
- Large range in (f, k) space
  - 10 kHz $< f <$ 10 MHz
  - 2 cm^{-1} $< k <$ 30 cm^{-1}



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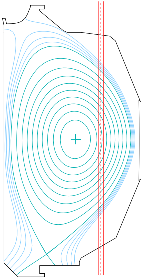
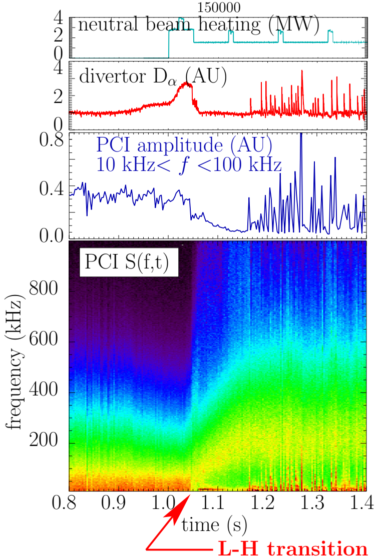
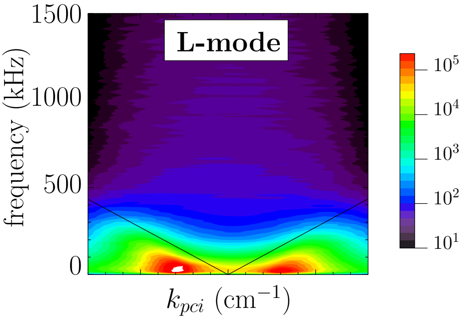




The $S(f,k)$ measured by PCI in DIII-D's ELM-free H-mode has highly *asymmetric* features with well-defined v_{ph}



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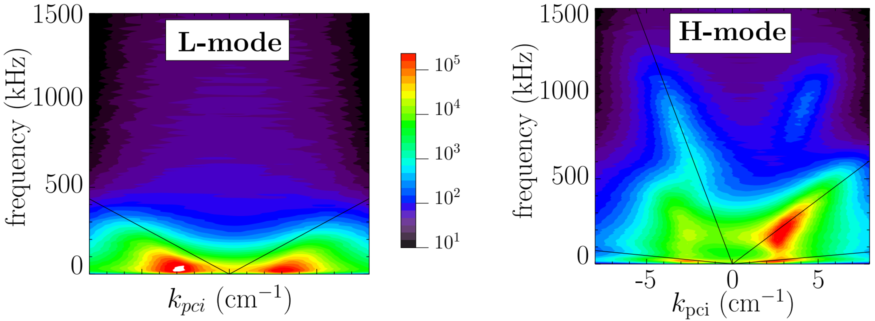
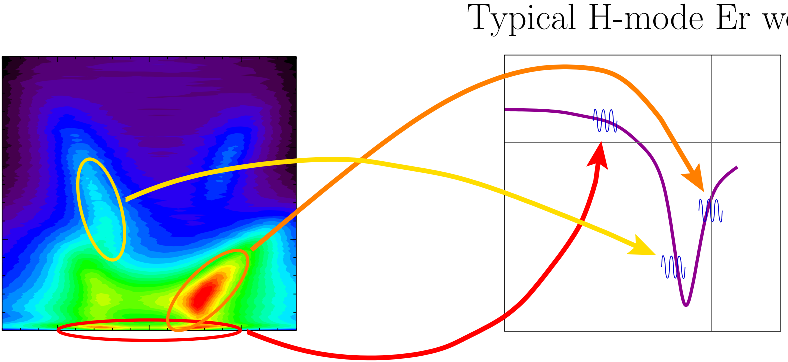


PCI's $S(f, k)$ structures suggest regions of strong localized edge turbulence*, begging theoretical validation

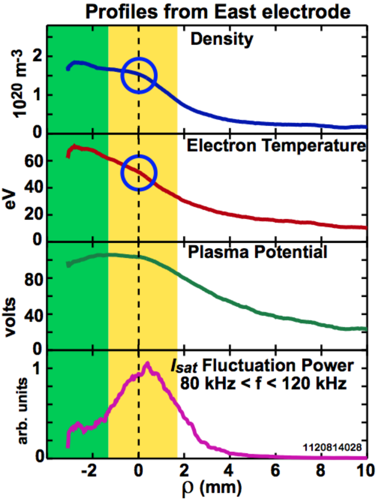


* J. C. Rost et al. in preparation (2013), and
J. C. Rost et al. TTF Workshop, Santa Rosa, CA (Apr. 9-12, 2013).

Conclusions and Future Work

- BOUT++ ideal linear growth rates are in good agreement with those from ELITE
- Both C-Mod and DIII-D are capable of accessing $\nu^* > 1$ and $\nu^* < 1$ regimes
- $\nu^* > 1$ simulations in BOUT++
  - EDA H-mode is a steady-state, high performance operational regime in C-Mod not explained by PB theory
  - Inclusion of C-Mod's resistivity drives RBMs that may explain the QCM and the resulting particle flux
  - Disagreement with MLP measurements indicates the need to include **drift wave** physics
- $\nu^* < 1$ simulations in BOUT++
  - PCI measures asymmetric turbulent spectra in DIII-D's ELM-free H-modes
  - Modeling with the gyro-Landau extension to BOUT++ will complement empirical knowledge

C-Mod's mirror Langmuir probe measurements show QCM lives in region with *positive* radial electric field*



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